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LCA of a biorefinery concept producing bioethanol, bioenergy, and chemicals from switchgrass

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Abstract

Background, aim, and scope The availability of fossil resources is predicted to decrease in the near future: they are a non-renewable source, they cause environmental concerns, and they are subjected to price instability. Utilization of biomass as raw material in a biorefinery is a promising alternative to fossil resources for production of energy carriers and chemicals, as well as for mitigating climate change and enhancing energy security. This paper focuses on a biorefinery concept which produces bioethanol, bioenergy, and biochemicals from switchgrass, a lignocellulosic crop. Results are compared with a fossil reference system producing the same products/services from fossil sources.

Materials and methods The biorefinery system is investigated using a Life Cycle Assessment approach, which takes into account all the input and output flows occurring along the production chain. This paper elaborates on methodological key issues like land use change effects and soil N_2O emissions, whose influence on final outcomes is weighted in a sensitivity analysis. Since climate change mitigation and energy security are the two most important driving forces for biorefinery development, the assessment has a focus on greenhouse gas (GHG) emissions and cumulative primary energy demand (distinguished into fossil and renewable), but other environmental impact categories (e.g., abiotic depletion, eutrophication, etc.) are assessed as well.

Results The use of switchgrass in a biorefinery offsets GHG emissions and reduces fossil energy demand: GHG emissions are decreased by 79% and about 80% of non-renewable energy is saved. Soil C sequestration is responsible for a large GHG benefit (65 kt CO_2-eq/a, for the first 20 years), while switchgrass production is the most important contributor to total GHG emissions of the system. If compared with the fossil reference system, the biorefinery system releases more N_2O emissions, while both CO_2 and CH_4 emissions are reduced. The investigation of the other impact categories revealed that the biorefinery has higher impacts in two categories: acidification and eutrophication.

Discussion Results are mainly affected by raw material (i.e., switchgrass) production and land use change effects. Steps which mainly influence the production of switchgrass are soil N_2O emissions, manufacture of fertilizers (especially those nitrogen-based), processing (i.e., pelletizing and drying), and transport. Even if the biorefinery chain has higher primary energy demand than the fossil reference system, it is mainly based on renewable energy (i.e., the energy content of the feedstock): the provision of biomass with sustainable practices is then a crucial point to ensure a renewable energy supply to biorefineries.

Conclusions This biorefinery system is an effective option for mitigating climate change, reducing dependence on imported fossil fuels, and enhancing cleaner production chains based on local and renewable resources. However, this assessment evidences that determination of the real GHG and energy balance (and all other environmental impacts in general) is complex, and a certain degree of uncertainty is always present in final results. Ranges in final results can be even more widened by applying different combinations of

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biomass feedstocks, conversion routes, fuels, end-use applications, and methodological assumptions.

Recommendations and perspectives This study demonstrated that the perennial grass switchgrass enhances carbon sequestration in soils if established on set-aside land, thus, considerably increasing the GHG savings of the system for the first 20 years after crop establishment. Given constraints in land resources and competition with food, feed, and fiber production, high biomass yields are extremely important in achieving high GHG emission savings, although use of chemical fertilizers to enhance plant growth can reduce the savings. Some strategies, aiming at simultaneously maintaining crop yield and reduce N fertilization application through alternative management, can be adopted. However, even if a reduction in GHG emissions is achieved, it should not be disregarded that additional environmental impacts (like acidification and eutrophication) may be caused. This aspect cannot be ignored by policy makers, even if they have climate change mitigation objectives as main goal.

Keywords Biorefinery · Bioenergy · Biochemicals · Switchgrass

1 Introduction and aim

1.1 Background

Our strong dependence on fossil fuels results from the intensive use and consumption of petroleum derivatives which, combined with diminishing petroleum resources, causes environmental and political concerns. There is clear scientific evidence that emissions of greenhouse gasses (GHG), such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), arising from fossil fuel combustion and land-use change as a result of human activities, are perturbing the Earth's climate (IPCC 2007). New renewable sources for energy and chemicals are therefore object of research and development activities. Electricity and heat can be provided by a variety of renewable alternatives (wind, solar, hydro, biomass, and others), while the alternative to fossil resources for production of transportation fuels and chemicals is only biomass.

Currently, transportation fuels based on biomass (i.e., biofuels) are identified as first and second generation biofuels. First generation biofuels are produced from sugar, starch, vegetable oil, or animal fats using conventional technologies. The basic feedstocks are often seeds and grains such as wheat, corn, and rapeseed. The most common types of first generation biofuels are bioethanol, biodiesel, and starch-derived biogas, but also straight vegetable oils, biomethanol, and bioethers may be included in this category. The main advantages of first generation biofuels are due to the high sugar or oil content of the raw materials and their easy conversion into biofuel, while the disadvantage is the competition with food and feed industries for the use of biomass and agricultural land.

Many biofuel production chains were analyzed by means of Life Cycle Assessment (LCA) in order to point out the environmental aspects affecting biofuels. With the exception of a few studies (Pimentel and Patzek 2005), most LCAs found reductions in global warming emissions and fossil energy consumption when the most common transportation biofuels are used to replace conventional diesel and gasoline (Punter et al. 2004; Kim and Dale 2005; von Blottnitz and Curran 2007). By contrast, considering other environmental aspects (acidification, eutrophication, ozone depletion, etc.) and including land use change effects in GHG balances, biofuels substituting fossil fuels may lead to increased negative impacts (Larson 2005; Zah et al. 2007; Farrell et al. 2006; Searchinger et al. 2008). These limitations are expected to be partially overcome by developing the so-called second generation biofuels which are produced from a variety of lignocellulosic non-food crops and residues (Cherubini et al. 2009a). Few LCA studies on second generation biofuels are currently available and they generally reveal better environmental performances than first generation biofuels (Stoeglehner and Narodoslawsky 2009; Jungmeier et al. 2007).

1.2 Biorefinery systems

In the near future, second generation biofuel facilities are expected to develop towards biorefinery concepts, where bioenergy, biochemicals, and biomaterials are co-produced along with transportation biofuels (EU 2006). Among the several definitions of biorefinery, the most exhaustive was recently formulated by the International Energy Agency Bioenergy Task 42 "Biorefinery" (IEA 2008): "Biorefining is the sustainable processing of biomass into a spectrum of marketable products and energy". The term biorefinery is raising importance in the scientific community and the concept is analogous to today's petroleum refinery, which produces multiple fuels and products from petroleum. Some biorefinery complexes and non-conventional biomass industries are already competitive in the market and many pilot and demo plants are running worldwide (most of them with the purpose to optimize the production of bioethanol and chemicals from lignocellulosic sources). A list of some existing commercial and pilot/demo plants can be found in (Cherubini et al. 2009b). Concerning the scientific literature about the application of LCA methodology to biorefinery systems, it is nowadays limited, and very few case studies exist (Cherubini and Ulgiati 2009; Uihlein and Schebek 2009). This study aims at addressing this topic, performing a thorough LCA of a biorefinery system which converts

switchgrass (a lignocellulosic crop) into bioethanol, bioenergy, and biochemicals (phenols). The assessment takes into account biomass cultivation, harvesting, processing, transport, conversion, and final use of products, along with important key methodological issues such as land use change effects and N_2O soil emissions. Since climate change mitigation and energy security are the two most important driving forces for biorefinery development, this work has a special focus on GHG and energy balances. Other environmental impact categories are investigated according to the Centrum voor Millieukunde Leiden (CML) method.

2 Materials and methods

2.1 Goal of the study

This work deals with an LCA of a biorefinery concept which produces bioethanol, electricity, heat, and phenols from switchgrass, a lignocellulosic crop. According to the classification method for biorefinery systems (Cherubini et al. 2009c), this concept can be labeled:

> C5/C6 sugars, biogas, lignin/pyrolytic oil biorefinery for bioethanol, electricity and heat, and chemicals from lignocellulosic crops

This system is a combination of several conversion technologies which are jointly applied in order to produce biofuels and material products from lignocellulosic biomass, within a biorefinery approach. The biorefinery system is compared with a fossil reference system which produces the same products/services from fossils: gasoline for the transportation service, heat from natural gas (instead of biomethane), conventional phenols from oil refinery, electricity from natural gas (average among Austrian power plants), and heat from heavy oil. The reference use for the cultivated land is agricultural set-aside land, i.e., land left unproductive and assumed to be tilled once a year. The functional unit of the assessment is the amount of biomass treated per year, i.e., 477 kt_{dry}/a of switchgrass (corresponding to 1.45 kt_{dry} biomass per day).

This study is modeled by means of the LCA software tool SimaPro 7 (http://www.pre.nl/simapro/default.htm) and selected literature references are used to estimate input flows, specific emissions, and land use change effects. Since climate change mitigation and energy independence are the main driving forces for future biorefineries, results focus on GHG and energy balance. The energy return on investment (EROI) is also calculated; this index is the ratio between energy out (i.e., the energy content of the products) and the non-renewable energy in (i.e., all the non-renewable energy inputs, direct and indirect, required along the full life cycle; see Hammerschlag 2006). In addition, the life cycle impact assessment shows results in other environmental categories, according to the CML method (CML 2 baseline 2,000 V. 2.03). This is a problem-oriented Life Cycle Assessment method developed by the Institute of Environmental Sciences of the University of Leiden (Heijungs et al. 1992). The most uncertain parameters (i.e., change in soil C pools and N_2O soil emissions) are then discussed in a sensitivity analysis.

2.2 System boundaries and fossil reference system

In Fig. 1, the simplified system boundaries for the biorefinery and fossil reference systems are shown. The biorefinery

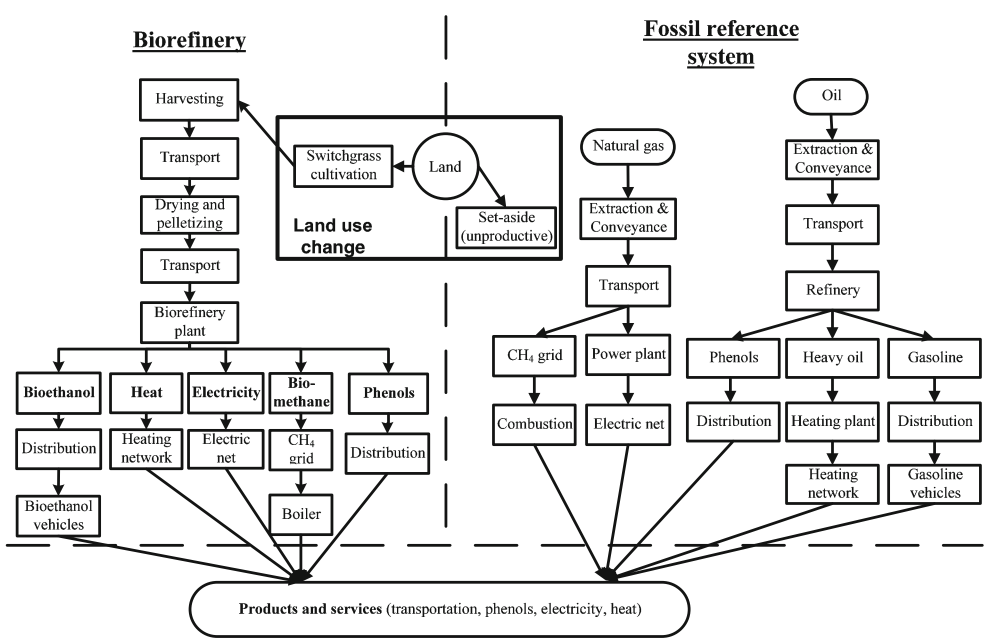

Fig. 1 Comparison between the production chain of the biorefinery and fossil reference systems

chain starts at the top of the diagram with carbon fixation from the atmosphere via photosynthesis, which results in crop growth. At the end, the biorefinery system supplies, products, and services: bioethanol, phenols, electricity, and heat. All input and output flows occurring along the full chain, for planting and harvesting the crops, processing the feedstock into biofuel, transporting and storing of feedstocks, distributing, and final use of biofuels are accounted for using a life cycle perspective. By contrast, the fossil reference system starts with consumption of non-renewable sources (i.e., fossil oil and natural gas), and its main life-cycle stages are the following: extraction and conveyance of raw materials, production of the raw fossil fuel, refining, storage, distribution, and combustion. Since production of the biomass feedstock requires land previously dedicated to other purposes, the reference system also includes an alternative land use (set-aside land), and the LCA effects of such a land use change are accounted for in the assessment.

The fossil-derived alternatives to biorefinery products are the following:

- Gasoline for the transportation service;
- Electricity from natural gas (average among Austrian power plants);
- Heat from heavy oil (industrial furnace);
- Phenols from oil refinery;
- Heat from natural gas (industrial furnace) instead of heat from biomethane (produced by the biorefinery).

The specific GHG and energy demand factors of these fossil-derived products are multiplied by the final quantities of products produced by the biorefinery: the final GHG emissions and cumulative primary energy demand of the fossil reference system can then be estimated.

2.3 Switchgrass production

Switchgrass (*Panicum virgatum*) is a lignocellulosic crop that offers many advantages to the developing bioenergy and biorefinery industries (Balat and Balat 2009). Like other high-yielding varieties of native prairie grasses, it has low nutrient demand, a diverse geographical growing range and high net energy yields, and offer important soil and water conservation benefits (Sokhansanj et al. 2009). Thanks to its deep fibrous system, switchgrass can enhance C sequestration in soils and improve soil quality (Downing et al. 1995; Mitchell et al. 2008). Several recent studies revealed that switchgrass is a promising lignocellulosic bioenergy crop: N fertilization does not increase soil surface CO_2 emissions despite slight increases in biomass production (Mulkey et al. 2006).

Once established, switchgrass takes 3 years to reach its full production potential. In this assessment, an average yield of 16 t_{dry}/ha per year is assumed (Smeets et al. 2009). Prior to cultivation, lime must be applied to reduce soil acidity and fertilizers used to enhance plant growth (Bullard and Metcalfe 2001). At harvest, switchgrass has a water content of 20% and its chemical and elemental composition can be found in (EERE 2009). The list of material and energy inputs required to produce switchgrass pellets to be used as feedstocks in biorefinery is shown in Table 1. The cultivation phase also includes sowing, tilling, spreading of fertilizers, harvesting, and baling. Switchgrass is harvested once a year, baled, loaded on trucks, and transported to the pellet facility. The feedstock is dried using heat from natural gas, while pellets are produced using electricity from grid (Austria). The feedstock is transported with 40-ton trucks for the following distances: 20 km from field to pellet facility and 100 km from the pellet facility to the biorefinery plant. This assumption represents the upper limit of transport distance under an economic feasibility perspective (Narodoslawsky et al. 2008).

2.4 Emission of N_2O and CH_4 from agricultural land

An important variable in LCA studies of biomass systems based on dedicated crops is the contribution to GHG emissions of N_2O, which evolves from nitrogen fertilizer application and organic matter decomposition in soil (Stehfest and Bouwman 2006). Emissions from fields vary depending on soil type, climate, crop, tillage method, and fertilizer application rates (Larson 2005). The uncertainties in actual emissions are magnified by the high global warming potential of N_2O, 298 times greater than CO_2.

Table 1 List of material and energy flows for cultivation, production, and delivery of switchgrass pellets

Flow	Unit/yr	Value	Source
Cultivation			
Seed	kg/ha	15	Bullard and Metcalfe 2001
Fertilizers			
N	kg/ha	112	Smeets et al. 2009
P	kg/ha	17	Smeets et al. 2009
K	kg/ha	54	Smeets et al. 2009
Lime	kg/ha	150	Bullard and Metcalfe 2001
Herbicides	kg/ha	2.5	Smeets et al. 2009
Emissions from land			
N_2O	g/gN	0.042	IPCC factor
CH_4	g/kgN	10	Delucchi and Lipman 2003
Processing and transport			
Drying	MJ/t_{water}	2.26	Smeets et al. 2009
Pelletizing	MJ_e/MJ	0.015	Gemis 2009
Transport	Mt*km	57.2	Assumption

It is possible to estimate N_2O emissions from land using default emission factors (IPCC 2006):

- Direct soil emissions of N as N_2O, at 1% of synthetic N application (mean value);
- Volatilization of N as NH_3, at a rate of 10% of total N of synthetic N application. One percent of N in NH_3 is then converted to N_2O;
- Leaching to groundwater as nitrate (30% of total N applied); 0.75% of it is converted to N_2O;

The resulting effect is that 1.325% of N in synthetic fertilizer is emitted as N in N_2O; this corresponds to an emission of 0.042 g N_2O per g N fertilizer applied. It should be noticed that one recent study suggests that these default emission factors may underestimate nitrous oxide emissions three- to fivefold (Crutzen et al. 2007). This topic is discussed in the sensitivity analysis, where different N_2O emission factors are used. The assessment also includes volatilization of NH_3 and leaching of nitrate, which affect other environmental impacts, like acidification and eutrophication.

Concerning CH_4 emissions, cultivation of agricultural and lignocellulosic crops can reduce the oxidation of methane in aerobic soils, and, thereby, increase the concentration of methane in the atmosphere (Ojima et al. 1993; Thustos et al. 1998). The reduction in soil uptake (oxidation) of methane is related both to the use of nitrogen fertilizer and cultivation type; the reduction in methane uptake is equivalent to an emission of methane from cultivated soils. A default value of 10 g CH_4/kgN for the emission of CH_4 from agricultural land is reasonable for most circumstances and results in a relatively small contribution to life cycle GHG emissions of the bioenergy chain (Delucchi and Lipman 2003).

2.5 Land use change effects

Generally, organic C is stored in three different pools: vegetation (including roots), litter, and soil. When changing land utilization, these storage pools can change until a new equilibrium is reached. This is an important aspect because of the large quantities of carbon in soil organic matter: these pools of carbon are so large that even relatively small percentage increases or decreases in their size can have relevance in the GHG balance. The potential to sequester carbon in soil is very site-specific and highly dependent on former and current agronomic practices, climate, and soil characteristics (Larson 2005). In general, cultivation of switchgrass on set-aside land improves soil quality and soil organic carbon (SOC). Several studies suggest that switchgrass grown for biomass feedstock production has the potential to substantially increase soil carbon stocks (Gebhart et al. 1994; Lal et al. 1998; Garten and Wullschleger 2000; Conant et al. 2001; Zan et al. 2001; Franck et al. 2004). Depending on the different conditions of soil, crop, and climate, there is a wide range in the estimation of the effective soil C sequestration rate. Paustian et al. (2006) state that converting land to grassland like switchgrass typically increases soil C at rates of 0.2–1.1 t C/(ha*a) (Paustian et al. 2006). Therefore, a C sequestration rate of 0.6 t C/(ha*a) is assumed in this assessment. Such an assumption is consistent with another study which revealed an average sequestration rate of 0.53 t C/(ha*a) over a 30-year-simulation period, with a total capacity limit of surface layer at 80 t C/ha (McLaughlin et al. 2002). The change in above ground carbon stocks are assumed to be zero because set-aside land contains negligible amounts of standing biomass, and switchgrass is harvested annually.

Since switchgrass yields are assumed to be 16 t_{dry}/ha per year, about 29.8 kha of land are required to meet biorefinery feedstock demand (i.e., 477 kt_{dry}/ha, the functional unit of the study): the total C uptake and stored in SOC is, hence, 17.9 kt C/a, which corresponds to a sequestration of 65.6 kt CO_2-eq/a.

According to Intergovernmental Panel on Climate Change (IPCC) guidelines, the payback time (or effect time) considered in this assessment is 20 years, which is the standard inventory time period for many bioenergy crops. After 20 years, it is assumed that the field reaches a new equilibrium and atmospheric CO_2 is no longer sequestered in soil organic matter. This means that the final GHG balance of the biorefinery system is not anymore influenced by CO_2 sequestration benefits. Therefore, final results distinguish two timeframes: GHG balance for the first 20 years (with CO_2 sequestration in soil) and GHG balance after the first 20 years (without CO_2 sequestration).

The SOC value of the starting condition (at year 0) is based on the average SOC content of soils in set-aside land calculated using the IPCC factors. These factors (under Austrian conditions of soil and climate) are the following:

$$SOC = SOC_{ref} \bullet F_{LU} \bullet F_{MG} \bullet F_I$$

SOC = soil organic carbon of set-aside land, to be determined;
SOC_{ref} = reference carbon stock; estimated value: 90 t C/ha (average between soils with high and low activity clay);
F_{LU} = stock change factor for land use or land-use change type; for set-aside land it is equal to 0.82;
F_{MG} = stock change factor for management regime; for set-aside land it is equal to 1.16;
F_I = stock change factor for input of organic matter; for set-aside land it is equal to 0.91.

The resulting value is SOC=77.90 t C/ha, which is the initial soil carbon stock when set-aside land is displaced by

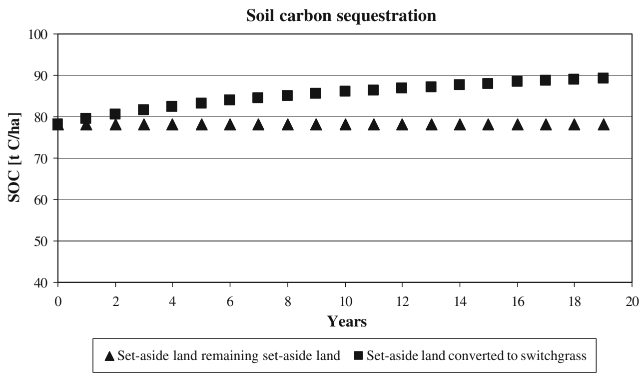

Fig. 2 Land use change: increase of SOC due to conversion of set-aside land to switchgrass cultivation

switchgrass crop. In 20 years, it is assumed an average C sequestration rate of 0.6 t C/(ha*a), which increases SOC up to 88.9 t C/ha (see Fig. 2). Afterwards, a new equilibrium is reached and the SOC remains constant.

2.6 Biomass conversion steps in the biorefinery

After cultivation, harvesting, and processing (i.e., drying from 20% to 10% water content and pelletizing), switchgrass is transported to the biorefinery plant where it is converted to bioethanol, bioenergy, and biochemicals (e.g., phenols). The feedstock is stored using a dry method, which needs 11.6 kWh_e per ton (Elsayed et al. 2003). The

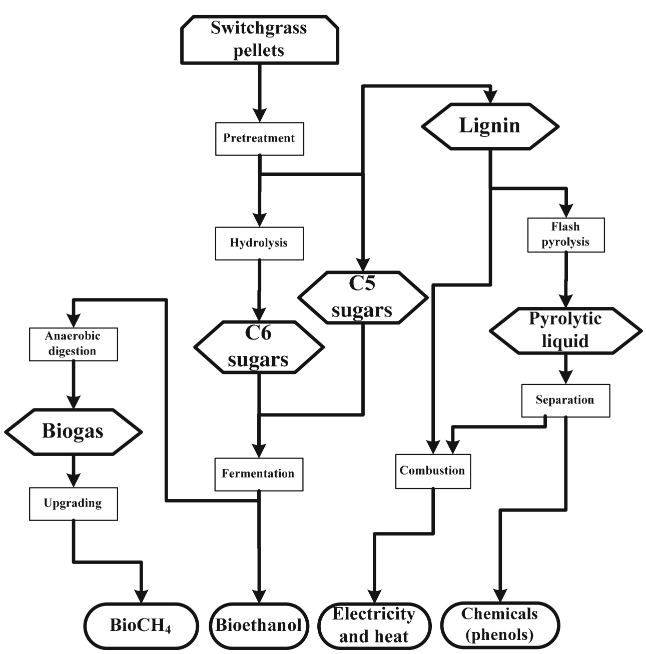

Fig. 3 Simplified process scheme of the switchgrass conversion steps in the biorefinery

conversion steps to which switchgrass pellets are subjected are the following (see process scheme in Fig. 3):

- Pretreatment (uncatalyzed steam explosion) of the raw material in order to depolymerize hemicellulose and separate lignin (Sun and Cheng 2002; Lynd 1996);
- Enzymatic cellulose hydrolysis to glucose monomers (Palmqvist and Hahn-Hägerdal 2000; Hamelinck et al. 2005);
- Fermentation and distillation of sugars to bioethanol (Hamelinck et al. 2005);
- Anaerobic digestion of wastewaters (Berglund and Börjesson 2006; Romano and Zhang 2008);
- Flash pyrolysis of lignin (20%) followed by phenol separation from the resulting pyrolytic oil (Zhang et al. 2007; Meister 2002);
- Final combustion (for heat and power production) of process residues, fraction of lignin that is not pyrolyzed (80%), pyrolytic char, and the remaining pyrolytic oil after phenol extraction (Senneca 2007; Gani and Naruse 2007).

The feedstock undergoes an uncatalyzed steam explosion, which occurs at a temperature of 160–260°C, with a reaction time of 2 min. During this stage, the C5 sugars in hemicellulose are hydrolyzed to xylose and arabinose with an efficiency of 85% (Hamelinck et al. 2005); arabinose is assumed to have the same conversion efficiency of xylose. Cellulose is hydrolyzed to glucose in the following enzymatic step with an efficiency of 90%; the remaining C6 polymers, galactan, and mannan, are hydrolyzed to galactose and mannose with an efficiency of 82% and 89%, respectively (Hamelinck et al. 2005). A fraction of cellulose (9%) is set aside for bacteria and enzyme cultivation and production. All the sugar monomers are then sent to fermentation while all the residues, together with lignin, undergo thermochemical treatment (combustion or pyrolysis). Concerning sugar fermentation, which occurs in a simultaneous saccharification and co-fermentation mode (with simultaneous fermentation of C5 and C6 sugars), ethanol conversion yields are 92.5% from C6 sugars and 85% from C5 sugars on a molecular basis (Hamelinck et al. 2005).

Bioethanol is finally distilled with an efficiency of 98%. Residues of these two steps are in water solutions and are anaerobically digested in order to produce biogas. These wastewaters have a total dry matter content of 85 kt_{dry} and generate biogas at an average rate of 6 GJ/t_{dry} (Berglund and Börjesson 2006). The produced biogas has a higher heating value of 24 MJ/m^3 and methane content of 60% (Alzate and Toro 2006). Methane emissions to the atmosphere during biogas handling are estimated to be 3.47 mg/MJ, and the upgrading of biogas

to biomethane (having a CH_4 content greater than 97%) by removing impurities and CO_2 needs 5% of the energy content of the biogas itself (Gemis 2009). The remaining digestate is disposed off in a wastewater treatment plant.

Concerning thermochemical treatments, 20% of lignin is subjected to flash pyrolysis, resulting in 75% pyrolytic oil (higher heating value 16 MJ/kg) and 25% charcoal (higher heating value 14 MJ/kg) (Zhang et al. 2007). The pyrolytic oil is a mix of different chemical compounds having an average phenol content of 32.3% (Zhang et al. 2007), which can be recovered at an efficiency of 50% (Scholze 2002).

The remaining pyrolytic oil after phenol separation is combusted with charcoal and the remaining lignin fraction (higher heating value 22.9 MJ/kg) and other residues (mainly unconverted sugar polymers, with a higher heating value assumed equal to 15.6 MJ/kg) to generate electricity and heat with an efficiency of 25.5% and 44%, respectively (De Feber and Gielen 2000). Ashes are disposed off to a monitored landfill.

This biorefinery system has an electricity demand of 0.83 GJ/t dry feedstock (Hamelinck et al. 2005), plus 0.03 GJ/GJ pyrolytic oil produced in flash pyrolysis (De Feber and Gielen 2000) and 0.54 GJ/t dry matter in wastewater for biogas production and upgrading to biomethane (Suh and Rousseaux 2001; Gemis 2009). The heat demand of the plant is 0.40 GJ/GJ bioethanol produced (De Feber and Gielen 2000) and 110 MJ/t dry matter in wastewaters (Berglund and Börjesson 2006). These energy needs are completely met by heat and power internally produced by combustion of lignin and residues. Information concerning auxiliary material used comes from Hamelinck et al. 2005. Emissions from combustion of process residues for generation of electricity and heat are estimated as well.

2.7 Distribution and final use

Bioethanol is distributed to fuelling stations (transport distance assumed: 100 km) where it is used to fuel passenger cars at a specific consumption of 2.45 MJ/km. Emissions for combustion of bioethanol in cars are estimated according to Halleux et al. (2008). Biomethane is fed to the national natural gas grid, by which it is delivered to final applications where it can replace natural gas in all its existing applications. It is assumed that biomethane will be burnt in a boiler and the resulting emissions are estimated. It should be noted that since the combustion of these biofuels (e.g., lignin and residues, bioethanol and biomethane) releases CO_2 which has a biological origin, it is not accounted for as a GHG. Phenols are transported for 50 km and used for producing resins; they are finally disposed off via incineration.

3 Results and discussion

According to the feedstock composition and the technological processes used, the biorefinery system produces the following products/service:

- Transportation service (bioethanol): 1,212 Mkm/a, equal to 110 kt/a or 2.97 PJ/a of bioethanol (corresponding to about 30% of feedstock energy value);
- Heat from biomethane: 179 TJ/a (2% of the feedstock energy value);
- Phenols: 1.57 kt/a or 50.3 TJ/a (0.5% of the feedstock energy value);
- Electricity (from combined heat and power; CHP): 93.0 TJ/a (1% of feedstock energy value);
- Heat (from CHP): 16 TJ/a (0.16% of feedstock energy value).

About 33.6% of the original energy content of the feedstock is found in final products. The remaining energy is lost during conversion processes and used to meet the biorefinery energy needs: about 85% of the electricity and 98% of the heat produced from CHP is internally used to run the biorefinery plant.

The fossil reference system, used for the comparison of final results, produces the same products/services from fossils.

3.1 GHG balance

Results of the GHG balance of the biorefinery (both for 1–20 years and after 20 years) and fossil reference systems are reported in Table 2, where the savings of the biorefinery systems are also shown.

The biorefinery system releases lower GHG emissions than the fossil reference system. While for both CO_2 and CH_4 emissions there is a decrease in airborne emissions (especially CO_2, thanks to sequestration of atmospheric carbon in soil for the first 20 years), emissions of N_2O are higher than in the fossil reference system. This is due to application of N fertilizers in agricultural soil, which stimulates higher N_2O soil emissions.

In the first 20 years, the biorefinery system benefits of atmospheric CO_2 sequestration in soil organic carbon; after 20 years, the soil reaches a new equilibrium and the effects of land use change does not occur anymore: atmospheric CO_2 is no longer sequestered in SOC and the final GHG emissions of the biorefinery system are higher.

Concerning GHG emission savings, they are estimated using different parameters: per year, per input biomass, and per hectare of agricultural land required to provide the feedstock (see lower part of Table 2). When results are normalized per input biomass, information about the possible savings from 1 t of dry feedstock comes out. This

Table 2 Total GHG emissions and savings of the biorefinery system for the first 20 years (with soil CO_2 sequestration) and after 20 years (without soil CO_2 sequestration)

	Unit/a	Biorefinery 1–20year	Biorefinery>20years	Fossil reference system
GHG emissions				
Total	kt CO_2-eq	60.5	126	281
CO_2	kt CO_2-eq	−8.6	58.2	266
N_2O	kt CO_2-eq	64.2	64.2	6.56
CH_4	kt CO_2-eq	4.86	4.86	8.91
GHG savings				
per year	kt CO_2-eq.	221	155	–
per year	%	79%	55%	–
per t_{dry} feedstock	t CO_2-eq./t_{dry}	0.46	0.33	–
per hectare	t CO_2-eq./ha	7.41	5.21	–

indicator is particularly important because renewable biomass is a finite resource. On the other hand, when savings are expressed per hectare of dedicated agricultural land, results are related to a fundamental limiting factor, the available land. This measure should be always used in studies where agricultural or lignocellulosic crops are used. In these cases, the GHG benefit per unit of land is a superior indicator from a land-use efficiency perspective. The possibility to show GHG savings using different parameters is extremely important when assessing the effectiveness of policy decisions on biomass energy in terms of their GHG balance. It is important to carefully set the functional unit and the normalization parameters, so that all GHG consequences of such decisions are included. Enhancing benefits with one indicator may result in opposite information when other parameters are used, and such tradeoffs can only be adequately addressed if all the possible parameters are taken into account.

Contributions to total GHG emissions of the biorefinery system are shown in Fig. 4. Feedstock production (including N_2O emissions from land) plays the largest role in determining the final GHG balance, while smaller contributions are due to transportation of pellets, emissions from combustion of residues for heat and power production, waste treatment, and manufacture of the auxiliary materials required to process the feedstock into final products. Concerning land use change, the replacement of set-aside land with switchgrass plantation results in a CO_2 sequestration in soils which has a positive effect (about 52% of total biorefinery emissions) on the final GHG balance of the first 20 years. As illustrated in Fig. 4, switchgrass production is responsible for about 80% of total GHG emissions. The main contributions to switchgrass production are:

- Emission of N_2O from agricultural land (40%);
- Processing and transport, including drying, pelletizing, and road transport (20%);
- Cultivation and harvest, including land preparation, seeds, herbicides, fertilizing, and harvesting (12%);
- Manufacture of fertilizers (28%).

Regarding the fossil reference system with which the biorefinery is compared, the largest fraction of total GHG emissions is originated from gasoline (86%), followed by electricity from natural gas (7%), heat from methane (5%) and then the others.

3.2 Energy balance

The primary energy demand of the biorefinery and fossil reference system is shown in Fig. 5. Results reveal that the biorefinery system needs a higher cumulative primary

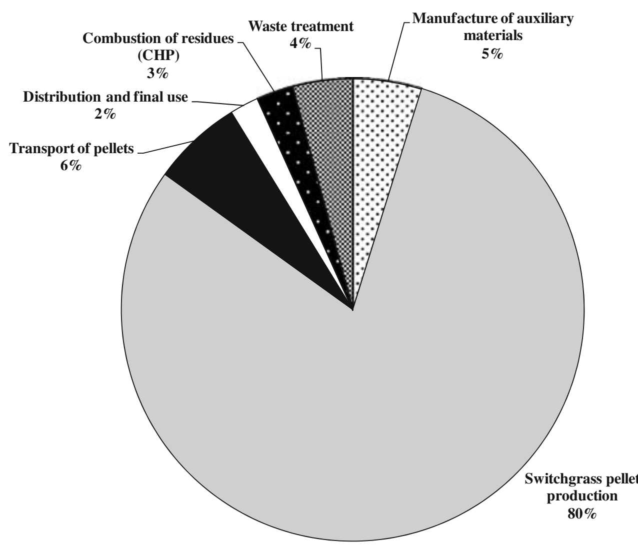

Fig. 4 Contributions to total GHG emissions after 20 years. For the first 20 years, contributions are identical but a reduction in CO_2 emissions equal to 65.6 kt CO_2-eq/a (52% of total emissions of the biorefinery system after 20 years) must be considered

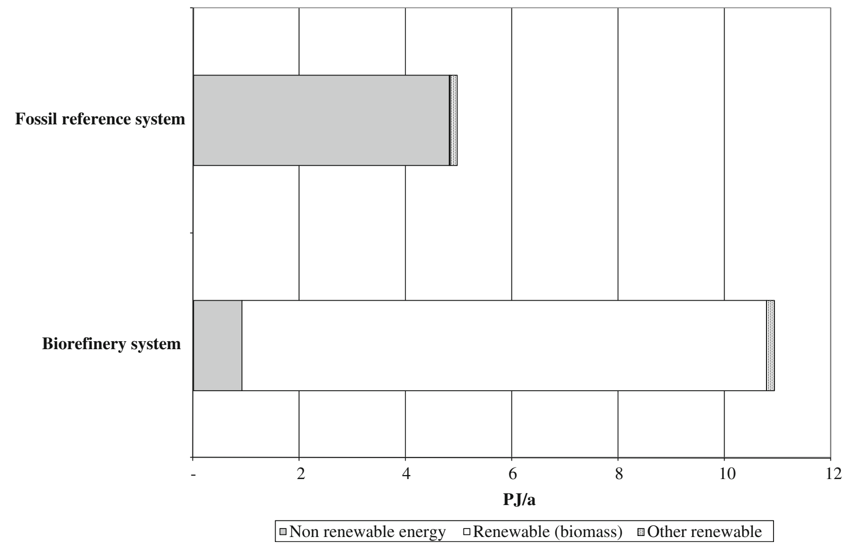

Fig. 5 Cumulative primary energy demand of the biorefinery and fossil reference systems. LUC effects do not affect the energy balance

energy demand than the fossil reference system (10.9 against 4.7 PJ), but it is mainly based on renewable energy (i.e., the energy content of the feedstock itself): the fossil energy demand of the reference system is drastically reduced, thus saving non-renewable energy sources. The estimated non-renewable energy savings are 3.6 PJ/a (about 80%), which corresponds to 7.64 GJ/t_{dry} and 122 GJ/ha.

The EROI is the ratio between energy out (i.e., the energy content of the products) and the non-renewable energy in (i.e., all the non-renewable energy inputs, direct and indirect, required along the full life cycle). When the EROI is equal to or lower than 1, that product becomes an "energy sink", and can no longer be used as a primary source of energy. This biorefinery system has an EROI index equal to 3.6: this means that the energy output of this system contains more than three times the non-renewable energy invested.

3.3 Other impact categories

Besides GHG and energy balances, the investigated biorefinery system was analyzed under other environmental impact categories. Results were calculated using the method "CML 2 baseline 2,000 V. 2.03" for impact assessment evaluation.

Results (for the 1–20 year biorefinery) are shown in Table 3 and compared in Fig. 6 where values are normalized to 100%. Biorefinery system has lower impacts in all categories except two: acidification and eutrophication. Acidification is due to switchgrass production (81%, mainly caused by atmospheric NH_3 emissions enhanced by N fertilizers) and biomass combustion for heat and power production (13%). Eutrophication is mostly given by N fertilization (88%). Emissions induced by fertilizer application also influence other environmental categories, like terrestrial and fresh water ecotoxicity, human toxicity, and others.

Since synthetic N fertilizers affect many impact categories, it is worth to investigate alternative strategies for N fertilizer application rates. The best option for reducing N_2O soil emissions is to use fertilizers more efficiently: the adoption of best fertilization practices could reduce agricultural N_2O emissions by 30–40% (CAST 2004). These practices include improved control of the amount, timing,

Table 3 Results of the CML impact assessment method for the first 20 years. After 20 years, CO_2 emissions of the biorefinery increase of 65.6 kt/a

Impact category	Unit/a	Biorefinery	Fossil reference system
Abiotic depletion	kt Sb eq	0.42	1.94
Global warming (GWP100)	kt CO_2 eq	60.5	281
Ozone layer depletion (ODP)	kg CFC-11 eq	10.5	31.2
Human toxicity	kt 1,4-DB eq	34.2	187
Fresh water aquatic ecotox.	kt 1,4-DB eq	4.08	16.8
Marine aquatic ecotoxicity	Mt 1,4-DB eq	22.8	50.1
Terrestrial ecotoxicity	kt 1,4-DB eq	0.35	0.62
Photochemical oxidation	kt C_2H_4	0.06	0.28
Acidification	kt SO_2 eq	1.23	1.17
Eutrophication	kt PO_4-eq	2.82	0.17

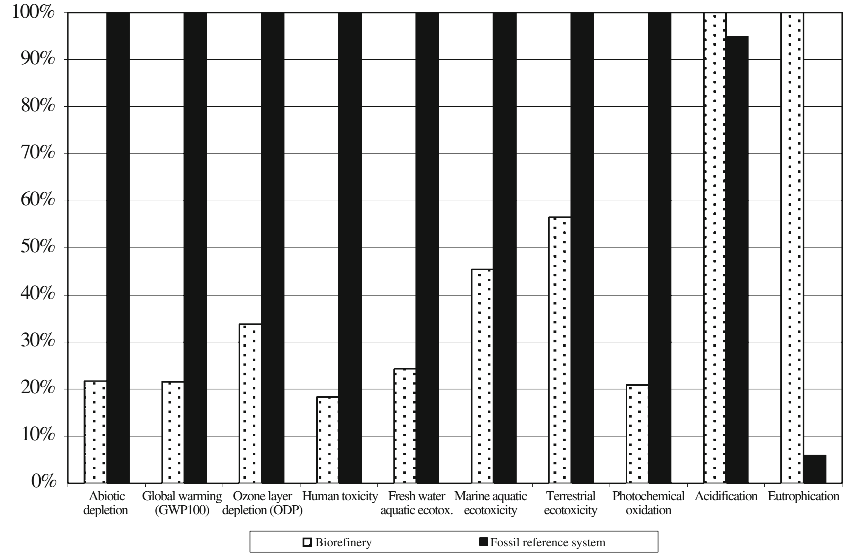

Fig. 6 Results of the CML impact assessment method

and placement of fertilizers, as well as using manure and inter-seeding with nitrogen-fixing species (Sanderson et al. 2001; Samson et al. 2005).

Results of Fig. 6 show that even if a biorefinery system achieves relevant GHG and fossil energy savings, it may cause additional environmental impacts than fossil-based systems in other impact categories. Despite most policy makers and initiatives assigning the highest priority to climate change mitigation strategies, other environmental impacts cannot be disregarded in order to avoid decisions based on partial, and sometimes even worthless, indications.

4 Sensitivity analysis

In this last LCA phase, an estimation of the effects of variations in key parameters to the outcome of the assessment is performed. This phase has the aim to establish a required degree of confidence in the results of the study relative to its overall goal. In particular, the objective of this step is to review the results of the analysis, identify the parameters which have the largest influence on the final results and check the accuracy of those data. Afterwards, these key parameters are changed according to different data sources or assumptions, and the outcomes compared. In the following sections, the most uncertain parameters are discussed.

4.1 N_2O emissions from agricultural land

N fertilizer application enhances N_2O emissions from soils. In this study, direct and indirect N_2O emissions due to synthetic fertilizer application were estimated according to IPCC guidelines. These factors revealed that 1.325% of N in synthetic fertilizer is emitted as N in N_2O. A recent paper by Crutzen et al. (2007) derived a different procedure for estimating this emission, and found out a value of 3–5%. This higher percentage is originated from the data compiled in two previous studies (Prather et al. 2001; Galloway et al. 2004) and is about three to five times larger than the IPCC factor. When this "extra" N_2O emission is included in GHG balances of biomass systems, Crutzen et al. (2007) state that the global warming benefits of most first generation biofuels are completely annulled. As a consequence, this study is frequently cited as evidence against the use of biofuels as an effective means for mitigating global climate change; by contrast, other studies claim that Crutzen et al. (2007) applied an uncertain approach, questionable assumptions, and inappropriate selective comparisons to reach their conclusions (North Energy 2008; RFA 2008).

In order to investigate this issue, factors from Crutzen et al. (2007) are also used, and the final results are compared.

The following N_2O emission factors are assumed (% refers to N in synthetic fertilizer emitted as N in N_2O):

- 1.325%, as derived from IPCC guidelines (and assumed in this analysis); i.e., 0.042 g N_2O/g N.
- 3%, lowest limit in Crutzen et al. (2007); 0.094 g N_2O/g N.
- 4%, average value in Crutzen et al. (2007); 0.13 g N_2O/g N.
- 5%, maximum limit in Crutzen et al. (2007); 0.16 g N_2O/g N.

Results are shown in Fig. 7. They point out that even with the highest N_2O emission factor, the total GHG emissions of the biorefinery system are lower than those of the fossil reference system (even if the savings are drastically reduced).

4.2 Soil C sequestration from switchgrass plantations

As pointed out in the previous results, the quantity of C sequestrated in soils by switchgrass plantations replacing set-aside land plays a key role in the GHG balance of the biorefinery. After a review of the available scientific literature, it was possible to summarize that converting land to grassland typically increases soil C at rates of 0.2–1.1 t C/(ha*a), thus, subtracting CO_2 from the atmosphere. Therefore, in this assessment, it has been assumed a C sequestration rate of 0.6 t C/(ha*a), corresponding to the average value. Other values tested in this sensitivity analysis are:

- 0.2 t C/(ha*a), corresponding to the lower value of the range;
- 0.6 t C/(ha*a), corresponding to the average value of the range (and assumed in this study);
- 1.1 t C/(ha*a), corresponding to the upper value of the range;

Results of this sensitivity analysis are shown in Fig. 8, where the final GHG balances obtained using the above-mentioned soil carbon sequestration rates are compared with the fossil reference system. Clearly, the larger is the soil carbon sequestration rate, the greater the CO_2 sequestrated from the atmosphere and subtracted to the overall CO_2 emissions of the system (which constantly decrease). When the maximum soil carbon sequestration rate is assumed, the biorefinery system becomes almost carbon neutral. Therefore, depending on the specific soil conditions and climate, the benefits deriving from replacing set-aside land with switchgrass plantations can strongly and positively affect the GHG balance of the biorefinery.

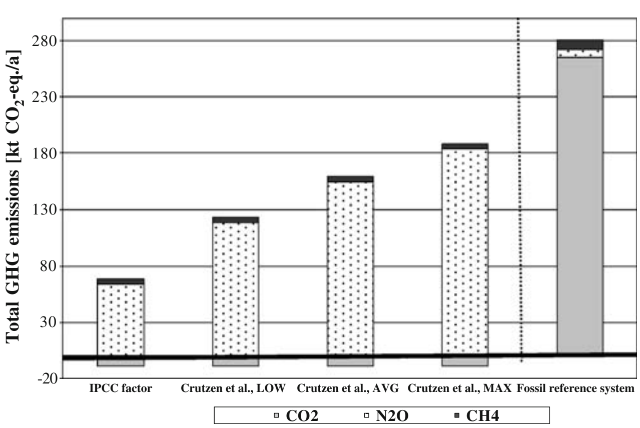

Fig. 7 Total GHG emissions of the biorefinery system using different N_2O emission factors from land

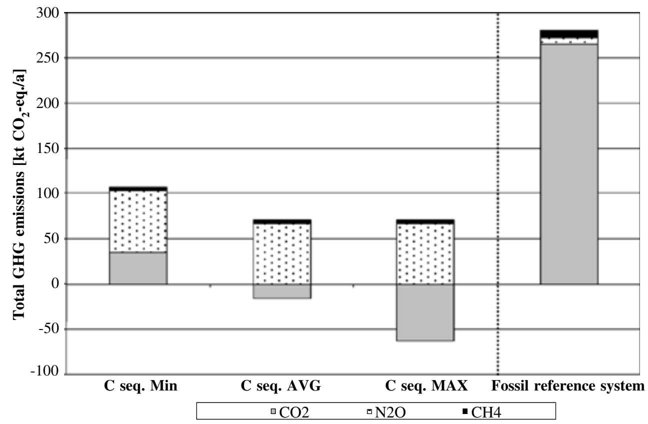

Fig. 8 Total GHG emissions of the biorefinery system using different C sequestration factors

5 Conclusions

The use of biomass as raw materials for bioenergy and biochemical production is encouraged by the need for a secure energy supply, a reduction of fossil CO_2 emissions, and a revitalization of rural areas. Biomass energy and material recovery is maximized if a biorefinery approach is considered, where many technological processes are jointly applied. The use of switchgrass as raw materials for biorefinery showed great potentials in the production of bioenergy and chemical products able to replace fossil-derived products and services. The LCA study performed in this work demonstrates that significant GHG and fossil energy savings are achieved when the biorefinery system is compared with a fossil reference system. In the first 20 years of activity, the biorefinery releases 60 kt CO_2-eq/a and requires 10.8 PJ/a of primary energy, of which 0.81 PJ/a fossil energy, while the fossil reference system releases 281 kt CO_2-eq/a and requires 4.7 PJ/a, of which almost 4.6 PJ/a fossil energy. Therefore, 79% of GHG emissions and 80% of fossil energy can be saved. This means that one hectare of land used to produce switchgrass can save almost 7.4 t CO_2-eq/ha. After 20 years, when the soil reaches a new equilibrium and atmospheric CO_2 is no longer sequestered, CO_2 emissions of the biorefinery system increase of 65 kt/a. Even if the biorefinery has higher primary energy demand than the fossil reference system, it is mainly based on renewable energy (i.e., the energy content of the processed feedstock): the provision of biomass with sustainable practices is then a crucial point to ensure a renewable energy supply to biorefineries. Investigation of other impact categories revealed that the biorefinery system has larger eutrophication and acidification potential impacts. Land use change effects and soil N_2O emissions play the biggest role in the final GHG balance, as shown in the sensitivity analysis.

6 Recommendations and perspectives

The use of switchgrass for this biorefinery is an effective option for replacing fossil-derived products and energy. It has emerged that biorefinery systems can mitigate climate change, reduce dependence on imported fossil fuels, and enhance cleaner production chains based on local and renewable sources. However, this assessment shows that an exact determination of the GHG savings (and all the other environmental impacts in general) of biorefinery systems is complex, due to the large uncertainty in some basic assumptions (like land use change and N_2O soil emissions) which depend on local and climate conditions. Ranges in final results can be even more widened by applying different combinations of biomass feedstocks, conversion routes, fuels, end-use applications, and methodological assumptions. Notwithstanding the difficulties and uncertainties in the estimation of land use change effects, any change (both decline and increase) in C stock of any pool should be always taken into consideration when estimating the GHG balance of a biorefinery system. Therefore, biorefinery systems based on dedicated crops should aim at minimizing the depletion of carbon stocks, in order to maximize the GHG emission savings. For instance, the perennial grass switchgrass enhances carbon sequestration in soils when established on set-aside land. This considerably increases the GHG savings of the system until a new soil equilibrium is reached. In addition, given constraints in land resources and competition with food, feed and fiber production, high biomass yields are extremely important in achieving high environmental impact savings, although use of chemical fertilizers to enhance plant growth can reduce these savings and increase the potential impact in other environmental categories. Some alternative fertilization strategies can be adopted, able to simultaneously maintain crop yield and reduce application rates through different management practices. Finally, even if a reduction in GHG emissions and fossil energy consumption is achieved, it should not be disregarded that additional environmental impacts (like acidification and eutrophication) may be caused. This aspect cannot be ignored by policy makers, even if they have climate change mitigation objectives as main goal.

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